A Quantitative Reliability, Maintainability and Supportability Approach for NASA's Second Generation Reusable Launch Vehicle

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ABSTRACT

The United States National Aeronautics and Space Administration (NASA) is in the midst of a 10-year Second Generation Reusable Launch Vehicle (RLV) program to improve its space transportation capabilities for both cargo and crewed missions. The objectives of the program are to: significantly increase safety and reliability, reduce the cost of accessing low-earth orbit, attempt to leverage commercial launch capabilities, and provide a growth path for manned space exploration. The safety, reliability and life cycle cost of the next generation vehicles are major concerns, and NASA aims to achieve orders of magnitude improvement in these areas. To get these significant improvements, requires a rigorous process that addresses Reliability, Maintainability and Supportability (RMS) and safety through all the phases of the life cycle of the program. This paper discusses the RMS process being implemented for the Second Generation RLV program.

1.0 INTRODUCTION

The 2nd Generation RLV program has in place quantitative Level-I RMS, and cost requirements [Ref 1] as shown in Table 1, a paradigm shift from the Space Shuttle program. This paradigm shift is generating a change in how space flight system design is approached. As a result, the program has set forth a system design philosophy that focuses on the system rather than the vehicle as shown in Figure 1.

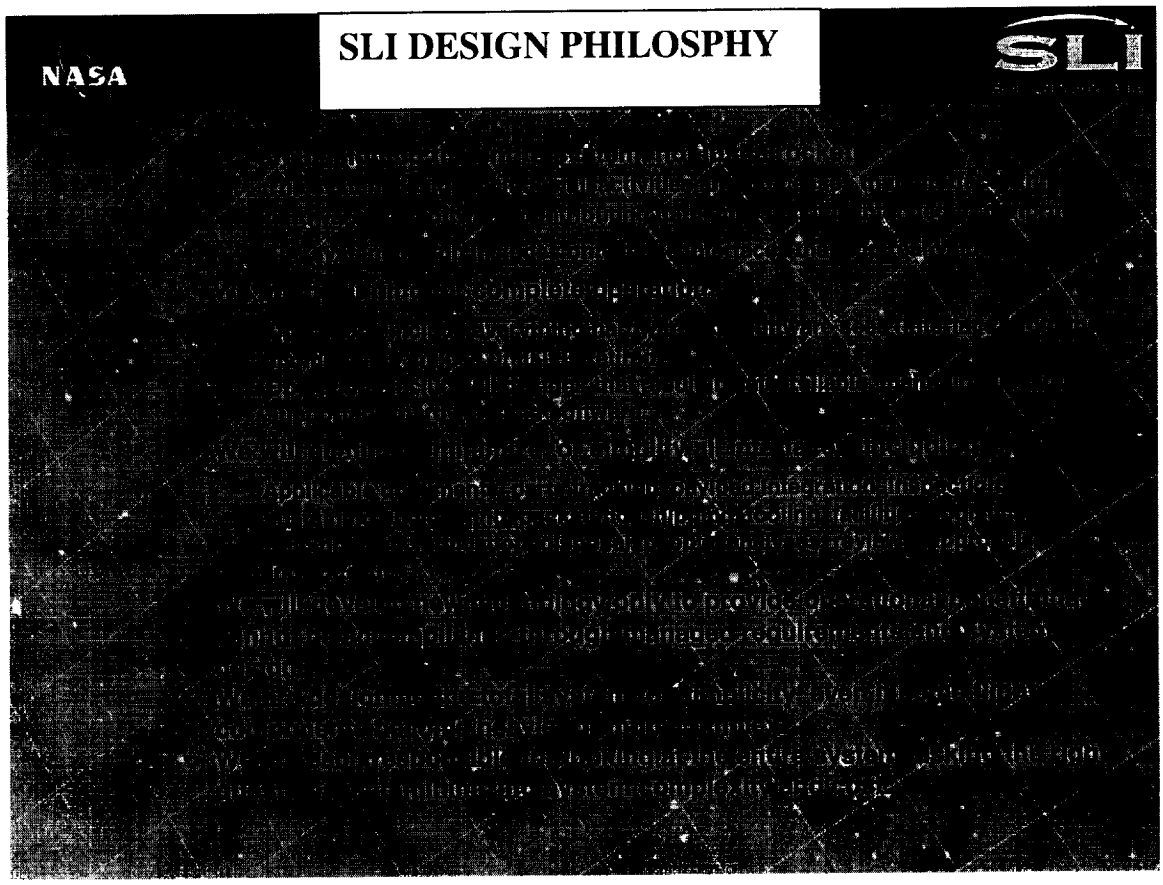

Figure 1. SLI Design Philosophy

In addition, the 2nd Generation RLV Program is trying to adopt an analysis based decision process as opposed to the traditional rule based system that has been applied to previous NASA Programs. Central to this process is the utilization of integrated RMS as discussed in the next section.

Requirement	Threshold	Objective
Improve RLV safety such that the total flight profile probability for loss of crew (LOC)	Must equal a probability of 1/5,000 or less	Should equal a probability of 1/10,000 or less
Provide access to space at an operational cost substantially below the current systems	For Human -- at least two thirds below that required to operate current systems For Cargo -- at least two thirds below that required to operate current systems	NA
Improve RLV reliability such that the probability for loss of mission (LOM) throughout the 2nd Gen RLV architecture's design life	Must provide a probability of 1/100 or less	Should provide a probability of 1/200 or less
Improve RLV robustness such that the probability for launching a payload within its scheduled launch opportunity	Must exceed 90%	Should exceed 95%

Table 1. Level 1 Safety and RMS Requirements

2.0 THE RMS INTEGRATED PROCESS

Reliability, maintainability, and supportability engineering are closely interrelated design support disciplines that provide essential systems analysis capability for reusable systems requiring high reliability, high availability, and low operational cost. Each RMS engineering discipline has been practiced in industry and within the Department of Defense for decades following standard methodologies. . In the In the 2nd Generation RLV Program, NASA is adopting the best-in-class integrated RMS practices from Department of Defense (DoD) and commercial industry to provide a cost effective solution. Specifically, the RMS disciplines will be brought together similar to the way they have been practiced in industry and in other government agencies through an integrated RMS Process under the direction of the RMS Program Lead.

2.1 Reliability Engineering

Reliability engineering is the application of mathematical and scientific principles to the practical end of achieving, cost effectively, the predictability required or desired in the level of functional output or performance. It supports design engineering in delivering a design that meets both mission reliability and availability requirements within cost constraints. Reliability engineering is the primary design-support discipline to help drive 2nd Generation RLV design to meet the quantitative Crew Safety and Mission Success requirements and to measure the capability of the launch vehicle to meet those requirements.

2.2 Maintainability Engineering

Maintainability engineering is the application of mathematical and scientific principles to the practical end of achieving easy, rapid, safe, and cost effective retention or restoration of function to specified levels of performance. It supports design engineering in delivering a design that is capable of having function restored to or retained at specification within availability and cost constraints. Maintainability engineering is the primary design-support discipline to help drive the design to meet allocated downtime or turnaround time for the Launch Availability requirement and then to measure the capability of the design to meet that requirement.

2.3 Supportability Engineering

Supportability engineering is the application of mathematical and scientific principles to the practical end of providing effective, economical support infrastructure (facilities, people, spares, etc.) for mission operations and the maintenance cycle. It provides product engineering design support through identification of support requirements (facilities, manpower, support equipment, etc.) for both mission operations and the maintenance cycle that will meet design reference mission requirements while satisfying both availability and recurring cost constraints. Supportability engineering is the primary

design-support discipline to help drive 2nd Generation RLV design to meet the operational support cost constraint. Supportability engineering provides fundamental input into the life-cycle cost breakdown structure for estimating the capability of the design to meet the operational support cost constraint.

2.4 The Second Generation RLV RMS Process

The RMS Process, illustrated in Figure 2, integrates the disciplines of reliability, maintainability, and supportability engineering through a specific sequencing of related RMS modeling and analysis tasks and through the flow of specific RMS data between the sequenced RMS tasks. The RMS Process also integrates the RMS modeling and analysis tasks, through the systems engineering process, with design engineering and with other engineering support disciplines such as cost and assurance.

The basic RMS Process begins with identification of failure states/events associated with the design, their severity, their causes, and their effects. This is done primarily through a Failure Modes and Effects Analysis (FMEA) of the design and is supported by Hazard Analyses and Human Factors Analyses. Next, reliability modeling and analysis develops reliability models of the failure modes/events and then arranges the individual models into a failure structure/logic model representing the ways in which system function may be lost. This logic model is executed analytically or through simulation to produce the primary output of the reliability modeling and analysis task: an estimation of system capability to meet reliability and safety figures of merit (FOM) [Ref 2] of Probability of Loss of Crew (PLOC), Probability of Loss of Vehicle (PLOV), and Probability of Loss of Mission (PLOM). At the same time, parameters from reliability models along with certain FMEA data serve as input into reliability-centered maintenance (RCM) analysis. The RCM analysis takes this input and runs it through an established RCM logic flow to generate an inventory of maintenance significant items (MSI) and basic maintenance actions required to retain or restore MSI function at or to specified levels of reliability/safety. The inventory of MSI and basic maintenance actions serves as primary input into both the maintainability and supportability modeling and analyses tasks that are closely interrelated and performed concurrently.

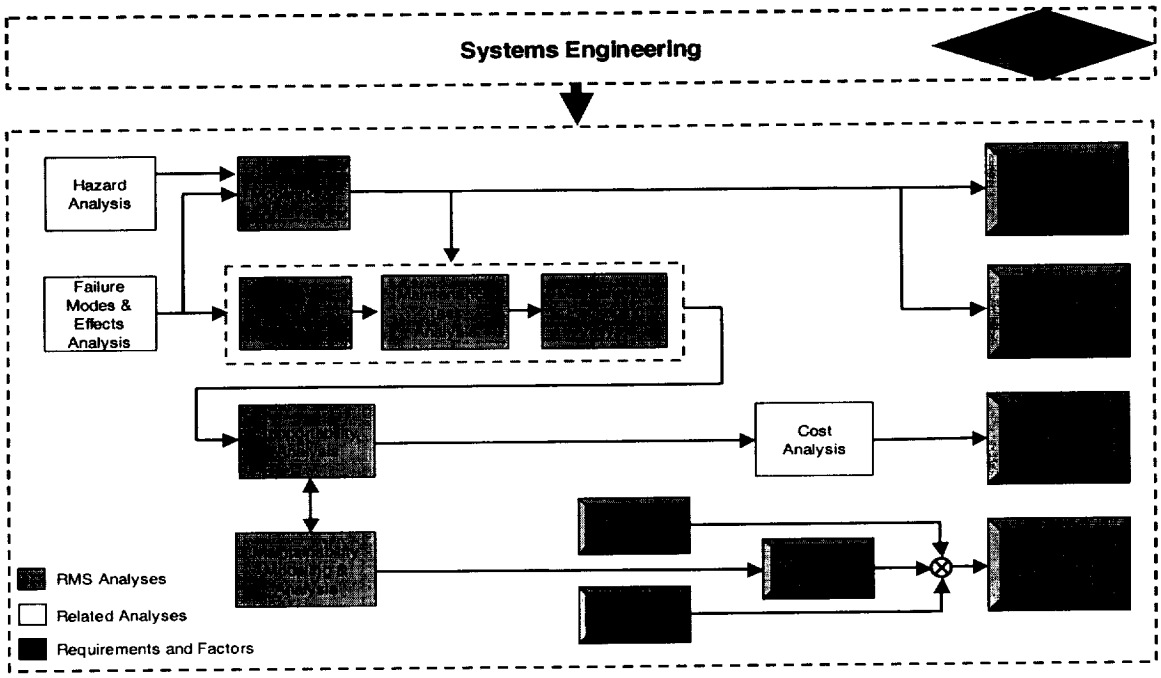

Figure 2. RMS Integrated Process

Maintainability modeling and analysis begins with the development of a top-level maintenance event sequence model initiated during conceptual design. It is continually decomposed to lower levels of indenture with increasing definition of system architecture, of maintenance and support tasks, and of maintenance packaging schemes. Once complete it provides a definitive maintenance and support (e.g., ground processing) flow model. Maintainability models estimating elapsed time for individual and grouped maintenance actions/events are developed concurrently at each level of indenture in the maintenance event sequence model. A downtime analysis is performed when required by executing the maintenance event sequence model analytically or through simulation. The downtime analysis estimates the capability of the maintenance and support system to deliver a space flight system ready for integration or flight within specified time constraints. This output at the vehicle level is combined with estimates of the start-up reliability of the launch vehicle and with estimates of the probability of the launch vehicle architecture not exceeding day-of-launch environmental constraints to produce an estimate of the launch availability FOM for the launch vehicle architecture.

Supportability modeling and analysis begins primarily with the maintenance task analysis that is initiated for each maintenance action output of the RCM analysis. This analysis is a decomposition of each maintenance action into all necessary steps for successful completion. A supportability analysis is performed concurrently with and on the maintenance task analysis to determine the required resource loading (facilities, personnel, support equipment, parts, etc.) for each maintenance action. Following the maintenance task analysis and concurrent supportability analysis, the individual maintenance actions are grouped into packaged sets of tasks that most effectively and

efficiently meet mission, reliability, and cost requirements. The final set of packaged maintenance actions are documented (e.g., Space Shuttle Organizational Maintenance Requirements Support Document (OMRSD)) for use by maintenance engineering. The supportability analysis is updated to reflect the packaged tasks and the output is provided to cost analysis in the form of total support resources per cost-breakdown-structure to support estimates of recurring cost.

2.5 The RMS Analyses Input/Output

Figures 3, 4, and 5 illustrate the reliability, maintainability, and supportability analyses and their respective inputs and outputs.

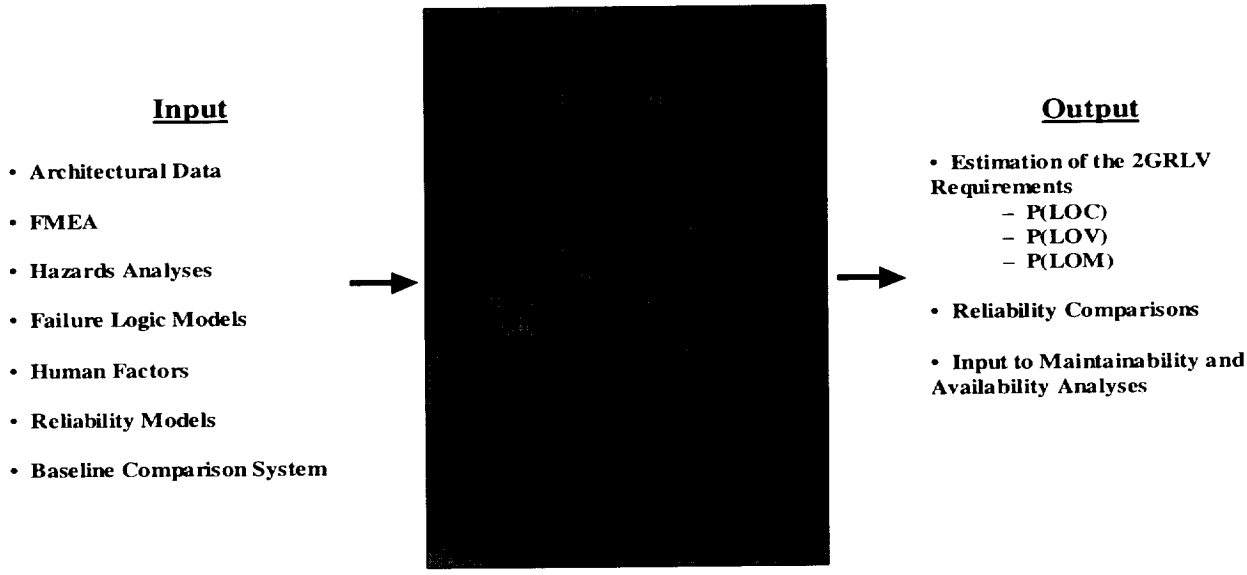

Figure 3. Reliability Analysis Flow Process

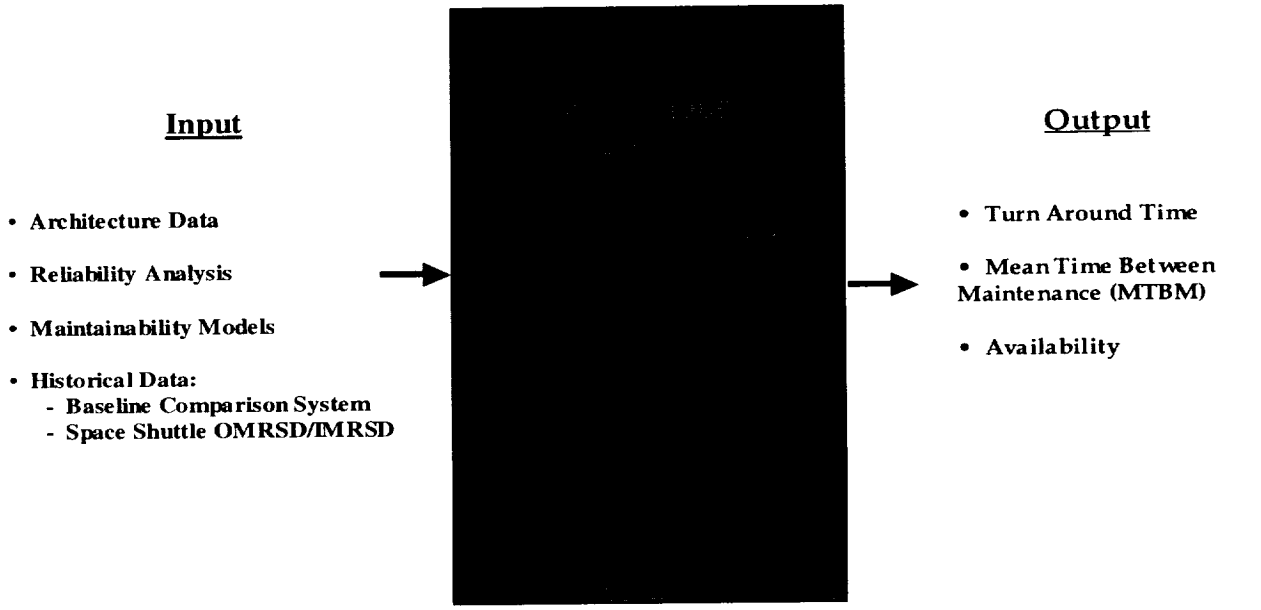

Figure 4. Maintainability Analysis Flow Process

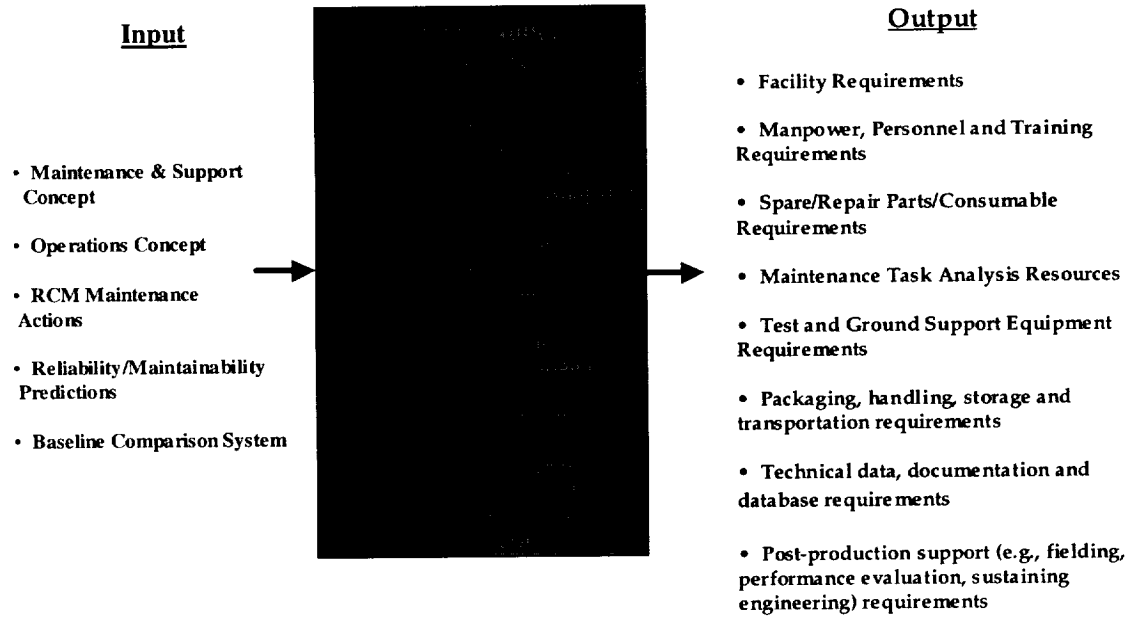

Figure 5. Supportability Analysis Process Flow

3.0 THE RMS MODELING AND ANALYSIS ENVIRONMENT

The 2GRLV Program has established a series of FOM's to serve as relative value indicator for the various proposed system architectures. The RMS Team is responsible for the FOMs associated with Loss of Crew (LOC), Loss of Vehicle (LOV), Loss of Mission (LOM) and Launch/Systems Availability (LA). In order to estimate the relative values associated with these FOMS, the RMS Team has established a modeling environment per 2GRLV Program Design Reference Mission [Ref 3].

The modeling environment is intended to establish the groundrules, assumptions and supporting data to be utilized in modeling and analyzing the various system architectures proposed to meet the requirements and goals of the 2GRLV Program. This environment establishes a common set of assumptions that will be applied by both the architectural contractors and by the NASA in-house modeling effort. Within this environment each of the architectural contractors and NASA will formulate models to describe the RMS relationships present within the proposed systems. Basic to this environments definition is that the "System" includes all element including flight, ground, support, etc. The System model must account for all of the factors impacting the performance of the system and must do so over all of the phases of the Program. It is incumbent on all members of the RMS community to recognize the interfaces that the RMS area has with other Program activities such as S&MA, Operations and Cost as shown in figure 5.

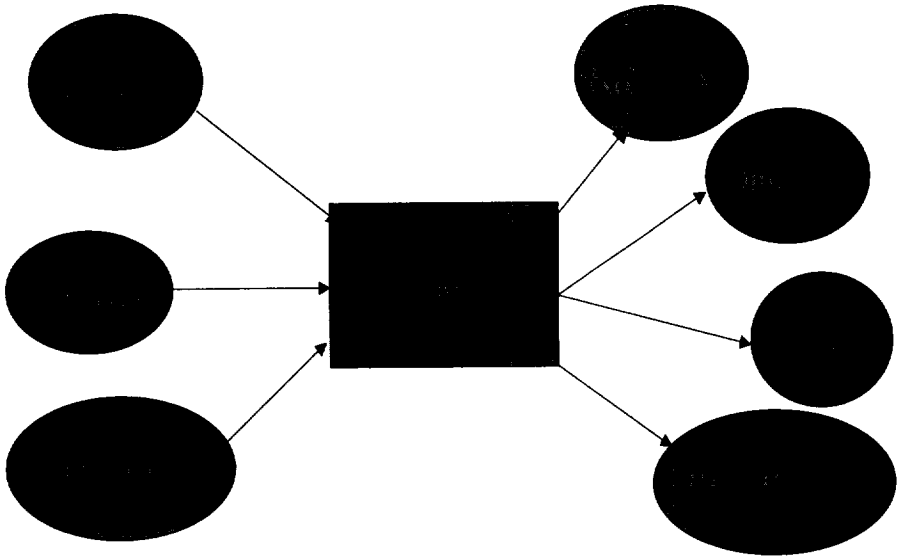

Figure 6. RMS Interface With Other System Activities

Each of the interrelated disciplines in Figure 6 provide various level of inputs and outputs over the life cycle of the project; for example, S&MA will provide detailed Hazards analysis and FMEA inputs once the design level has been defined to support these analyses. Prior to development of these analyses modeling will be performed on a more

parametric basis. The relationship between the various disciplines is dynamic in nature and will involve high degree of feedback management. Figure 7 illustrates some of the various interdependent elements which each of the various areas will be modeling.

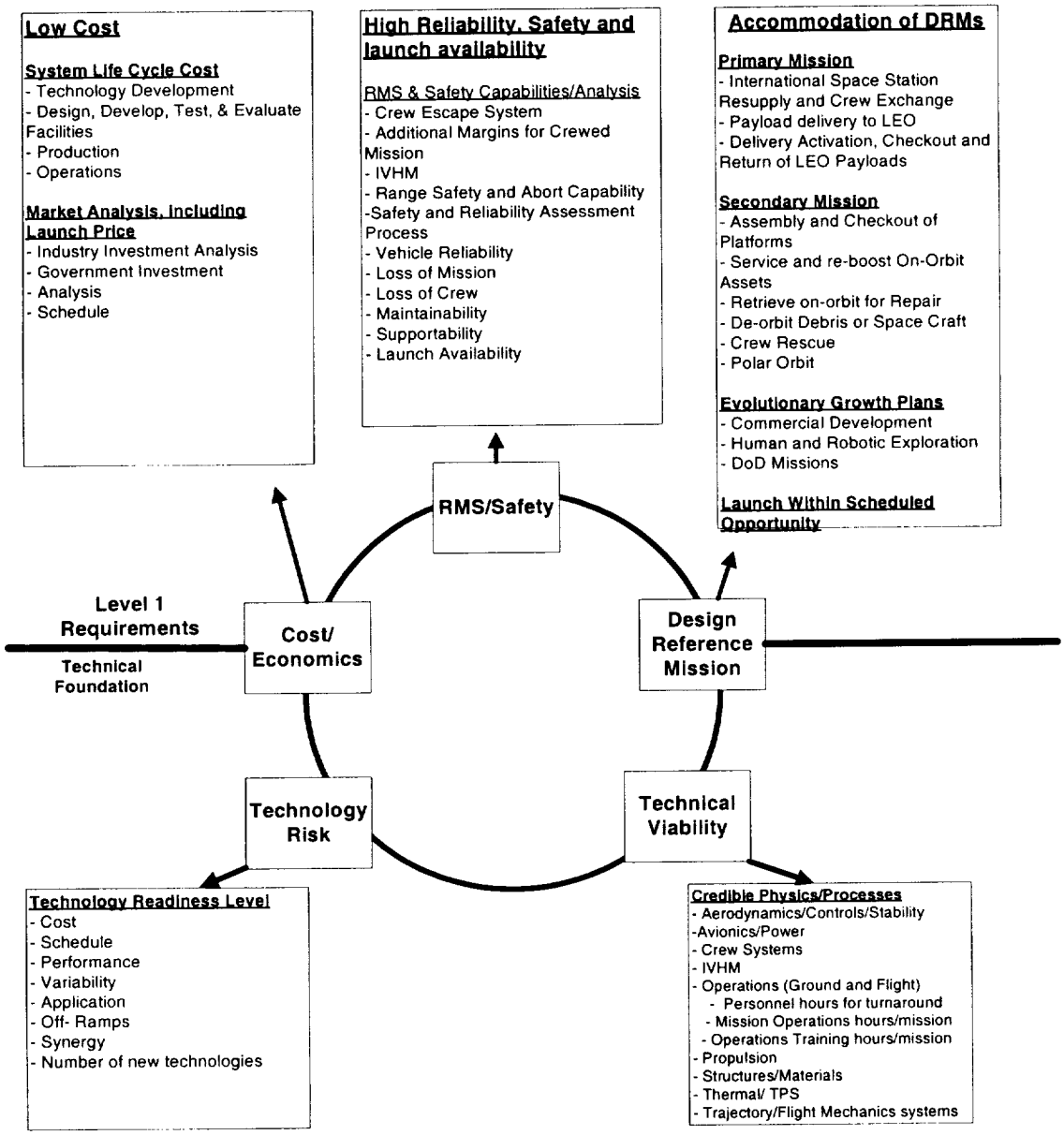

Figure 7. Criteria Addressed by the Systems Analysis Process

RMS Engineering within the 2 GRLV Program functions as an element of the SE&IO Organization. As an element of the SE&IO organization the RMS Team is integrated within the analysis and trades environment being executed by the 2 GRLV Program. The RMS Team draws on the common data dictionary utilized to perform all systems analyses. The outputs of the RMS analysis process become inputs to the common data dictionary and, as such, are reflected in interfacing analyses. The RMS Modeling and Analysis activity functions as an integral part of the 2GRLV Advanced Engineering Environment. This environment will evolve over time to reflect increasing level of both model and data fidelity. Figure 8 illustrates some of the key elements of this modeling environment. Each of the various modeling processes is linked to allow for an interdependence of the various analysis products.

At the present stage of modeling fidelity the reliability calculations are performed utilizing the Flight-oriented Integrated Reliability and Safety Tool (FIRST) Model and the maintenance and supportability is calculated utilizing the NROC Model. These modeling tools are focused on the conceptual design phase of the program. As the program moves into the preliminary design phase these models will be supplemented by more detailed modeling techniques. These techniques will be utilized for both total systems analysis and for focused lower level trade studies.

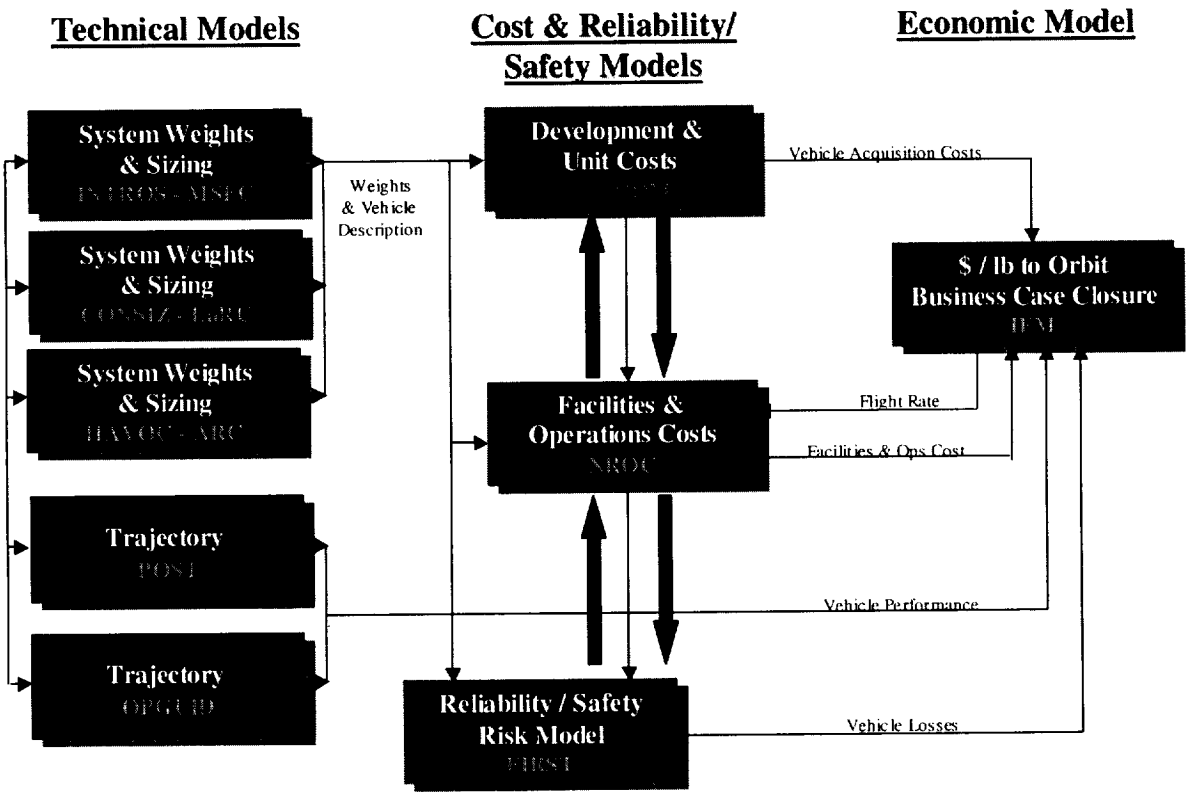

Figure 7. Integrated Modeling Environment

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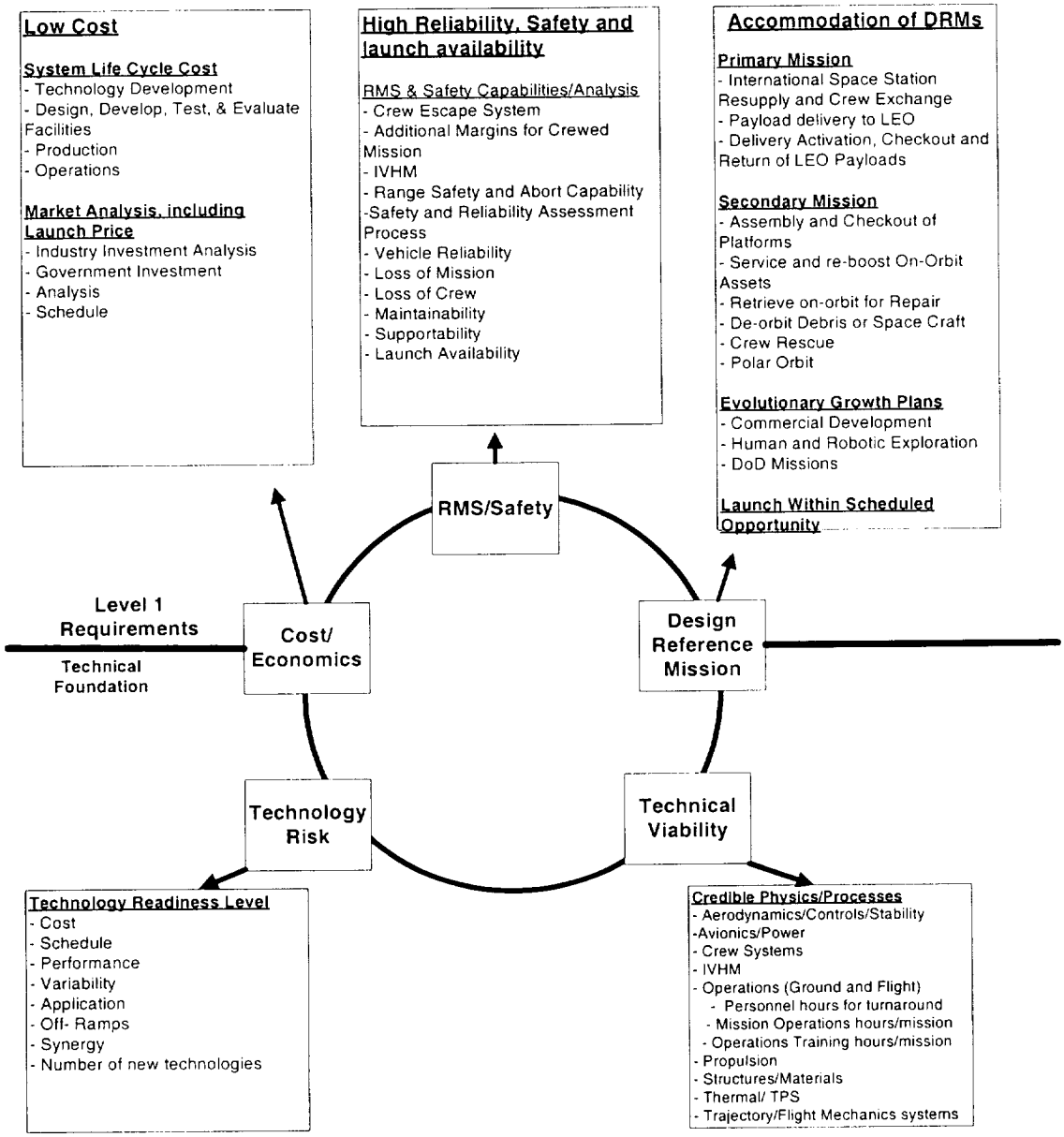

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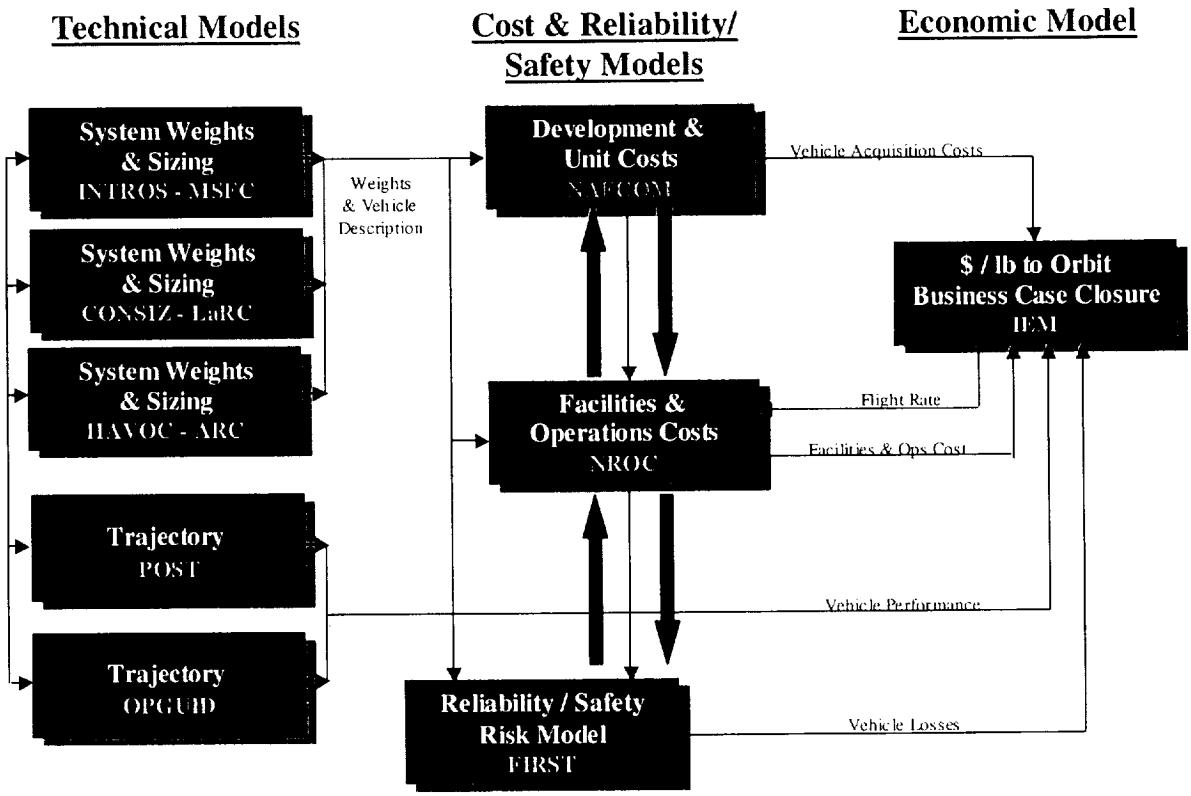

Figure 7. Integrated Modeling Environment

4.0 CONCLUDING REMARKS

In this paper we have discussed NASA's new integrated RMS approach that is consistent with the program system design approach. An approach that is based on a well-defined systems engineering analyses and processes, which, for the first time includes safety, reliability, maintainability, supportability and life cycle cost at the conceptual stage as part of system trades. This innovative approach provides the pathway for a risk based and analysis based decision process that is necessary to achieve NASA's goal of significantly improving safety and reducing cost. A goal that should greatly enhance the prospects for manned space flight in the future.

REFERENCES

1. "2nd Generation Space Transportation Architecture Level 1 Requirements"' MSFC-RQMT-3221 Rev A, April 26, 2002

2. "2GRLV-DOC-016, Rev. B, "2GRLV Figures of Merit (FOMs)", August 2, 2002.

3. "2GRLV-DOC-010, Rev. B, "2GRLV Program Design Reference Missions", May 1, 2002.

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Life Cycle Systems Engineering Conference

Nov 6 – 7 , 2002 at Redstone Arsenal, Alabama

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Dr. Charles Daniel

Prince Kalia

AGENDA

- Background
- Program Design Philosophy
- 2nd Generation RLV Requirements
- The RMS Integrated Process
- Reliability Analysis Flow Process Chart
- Maintainability Analysis Flow Process Chart
- Supportability Analysis Flow Process Chart
- RMS Analysis and Modeling Environment
  - RMS Interface with other System Activities
  - Criteria Addressed by the Systems Analysis Process
  - Integrated Modeling Environment flow diagram
- Conclusion

Background

- NASA's Space Launch Initiative (SLI) Team is in the midst of designing system for Second Generation Reusable Launch Vehicle (2GRLV) with very ambitious goals to improve its space transportation capability:
  - Significantly Safer and Reliable System than the present Space Shuttle
  - Significantly cheaper launch transportation system

The SLI Design Philosophy

- We are designing the entire system, not just a rocket:
  - The system design includes all activities and processes that interface with hardware and software, contributing to the mission it is intended to perform.
  - The system design includes only those interfaces that add real value.
- We are designing for complete operations:
  - Operations include everything hardware and software sees (interface) from the moment it is an idea until it is retired.
  - Operations include all designs that result in safe, reliable, maintainable, and supportable hardware and software.
- We will eliminate, minimize, or simplify all interfaces, including:
  - Applicable documents, parts tracking, payload integration, inspection, sustaining engineering, packaging, shipping, tooling, facilities, logistics, training, test, verification, disposal, people, analyses, reviews, approvals, and so forth.
- We will develop new technology only to provide operational benefit that cannot be accomplished through managed requirements and system design.
- We are designing the total system for simplicity, even if some flight components become heavier or more complex.
- We are each responsible for looking at the entire system, asking the right questions, and minimizing system complexity and cost.

2nd Generations RLV RMS Requirements

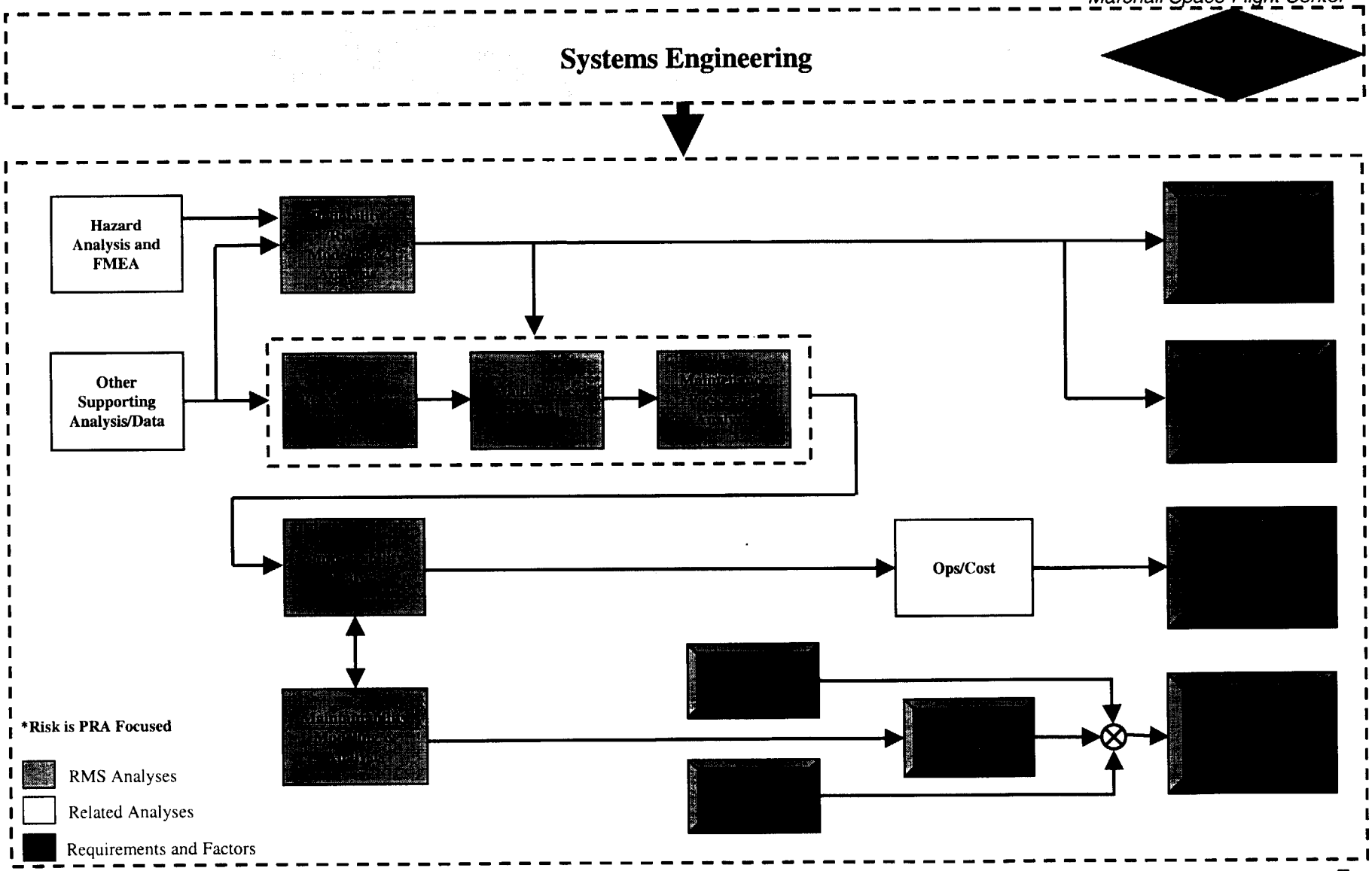
Requirement	Threshold	Objective
Improve RLV safety such that the total flight profile probability for loss of crew (LOC)	Must equal a probability of 1/5,000 or less	Should equal a probability of 1/10,000 or less
Provide access to space at an operational cost substantially below the current systems	For Human -- at least two thirds below that required to operate current systems For Cargo -- at least two thirds below that required to operate current systems	Same as Threshold
Improve RLV reliability such that the probability for loss of mission (LOM) throughout the 2nd Gen RLV architecture's design life	Must provide a probability of 1/100 or less	Should provide a probability of 1/200 or less
Improve RLV robustness such that the probability for launching a payload within its scheduled launch opportunity	Must exceed 90%	Should exceed 95%

Level I Requirements

The Integrated Reliability, Maintainability, and Supportability (RMS) Process

- NASA is adopting best-in-class integrated RMS practices from Department of Defense (DoD) and Commercial Industry to provide system analysis capabilities and trade studies.

The Integrated Reliability, Maintainability, and Supportability (RMS) Process

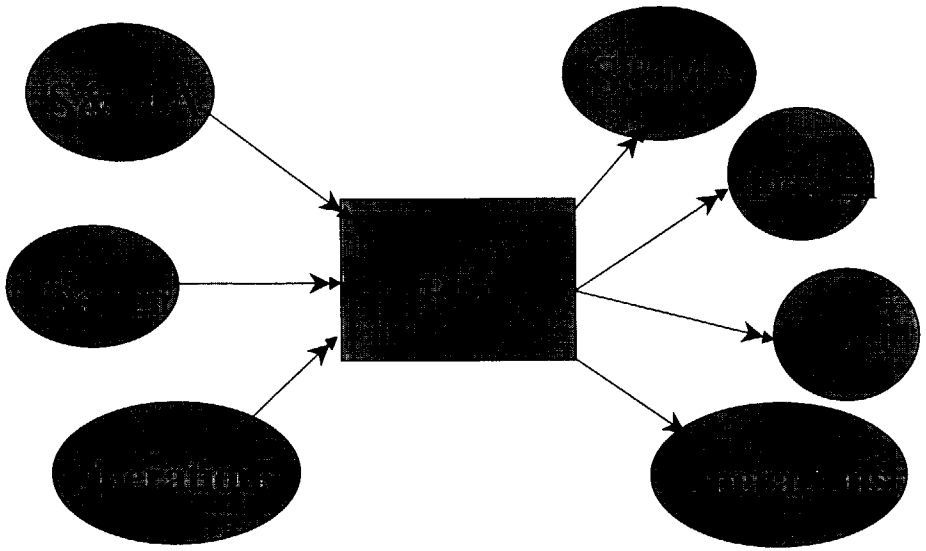


RMS Process Flow Chart

How Integrated RMS Process Works

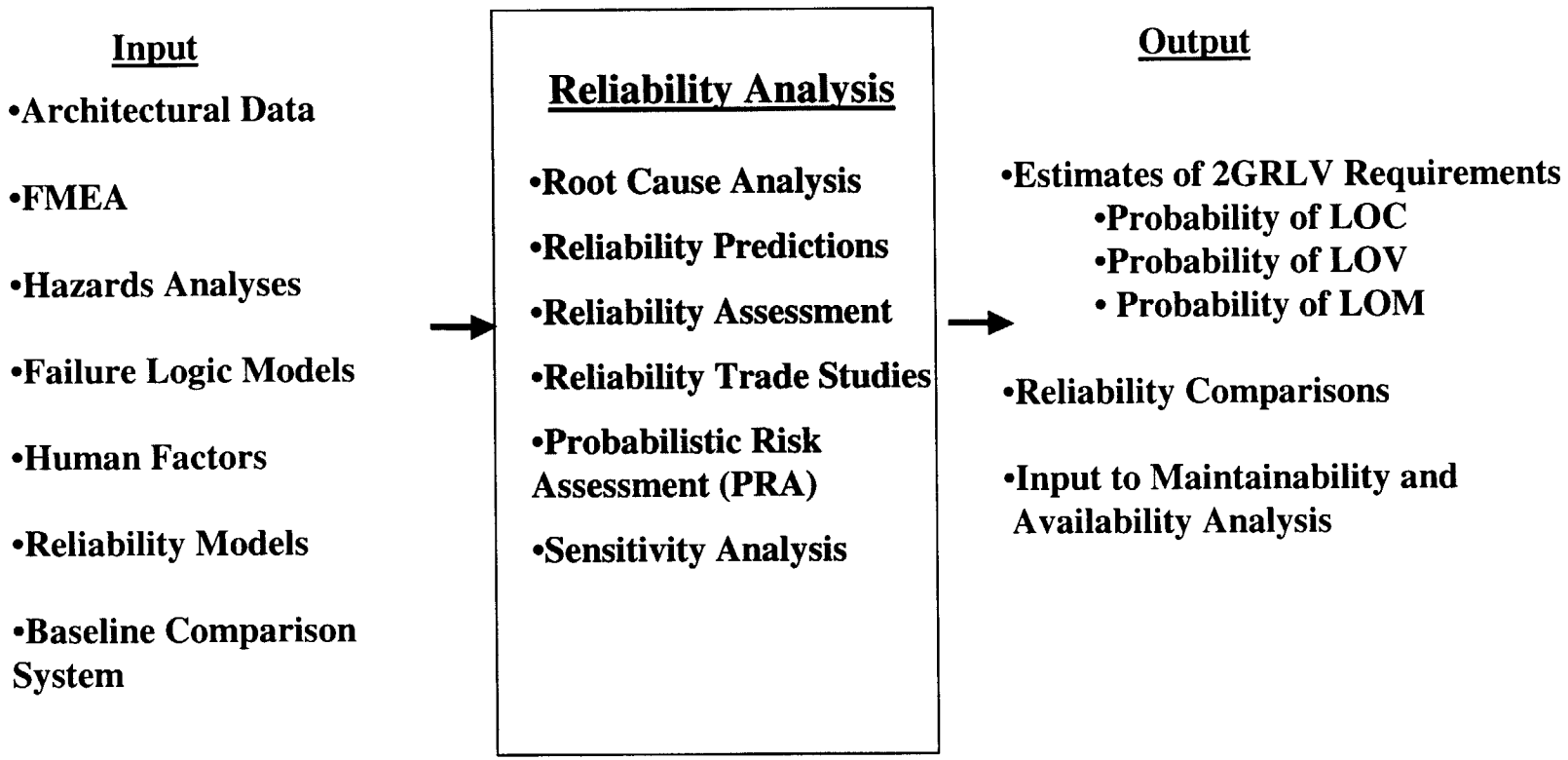
- RMS is a integrated systems engineering process to meet systems design philosophy for a significantly safer, reliable and lower Life Cycle Cost solution

- RMS analysis is integrated with input from Design, Safety and Mission Assurance (S&MA), and Operations and provides integrated RMS analysis output to all these disciplines and cost

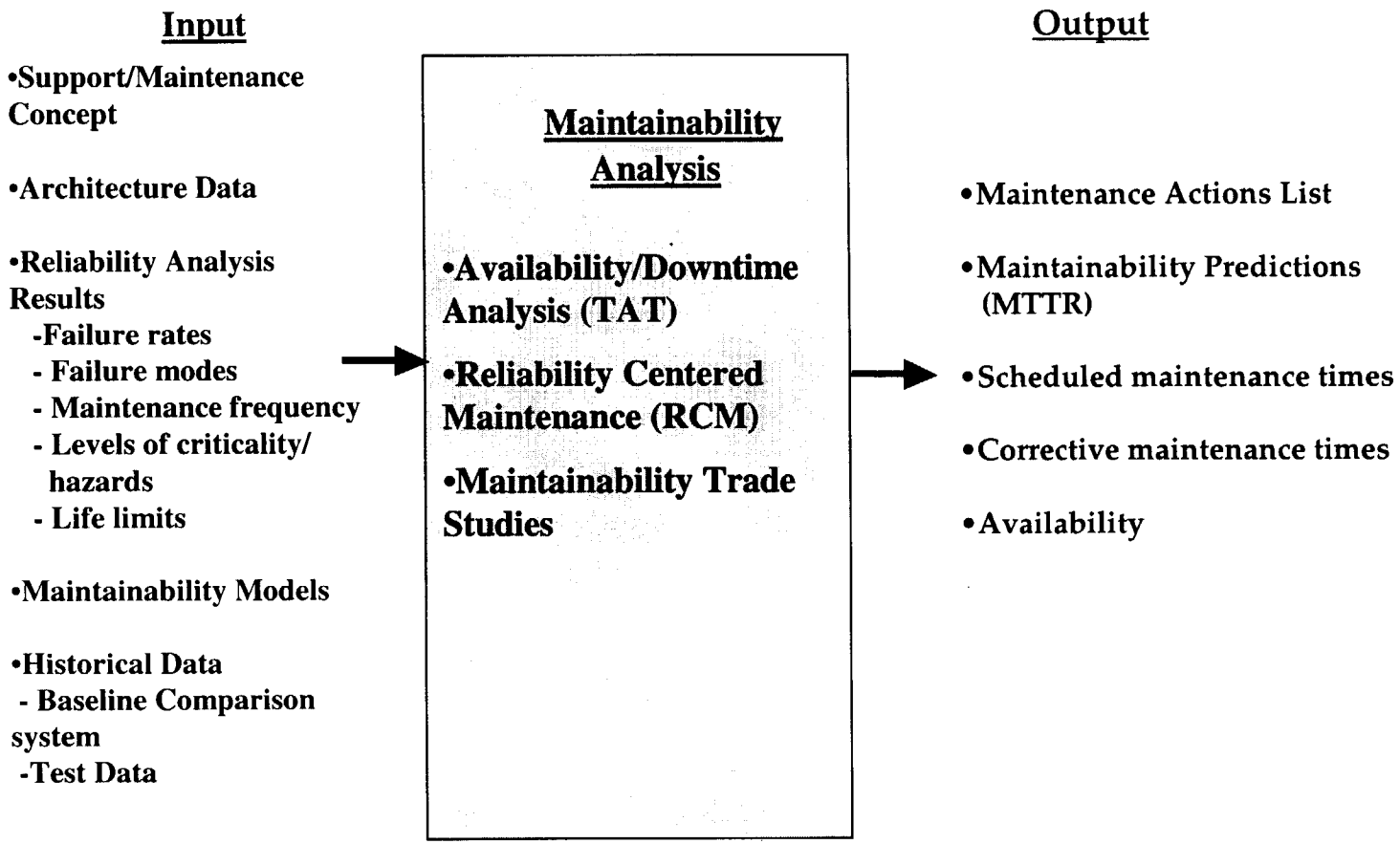


RMS Interface with other System Activities

Reliability Analysis Flow Process Chart (Input-Output)



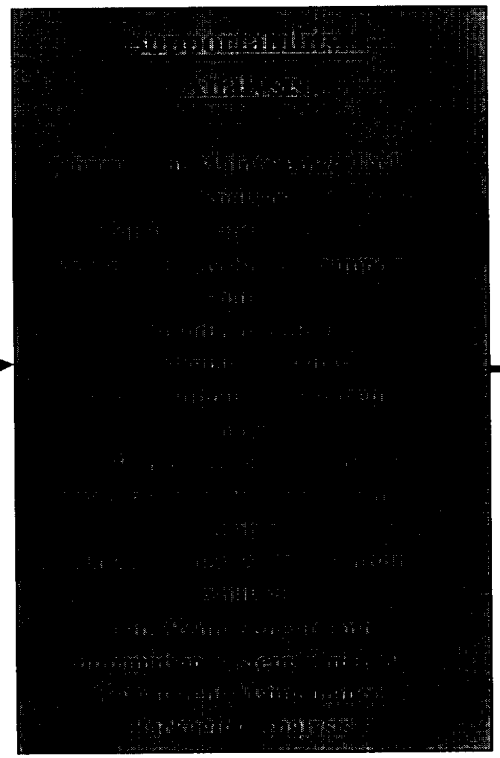
Maintainability Analysis Flow Process Chart
Input-Output



Supportability Analysis Flow Process Chart input-output

Input

- Maintenance & Support Concept
- Operations Concept
- RCM Maintenance Actions
- Reliability/Maintainability Predictions
- Baseline Comparison System



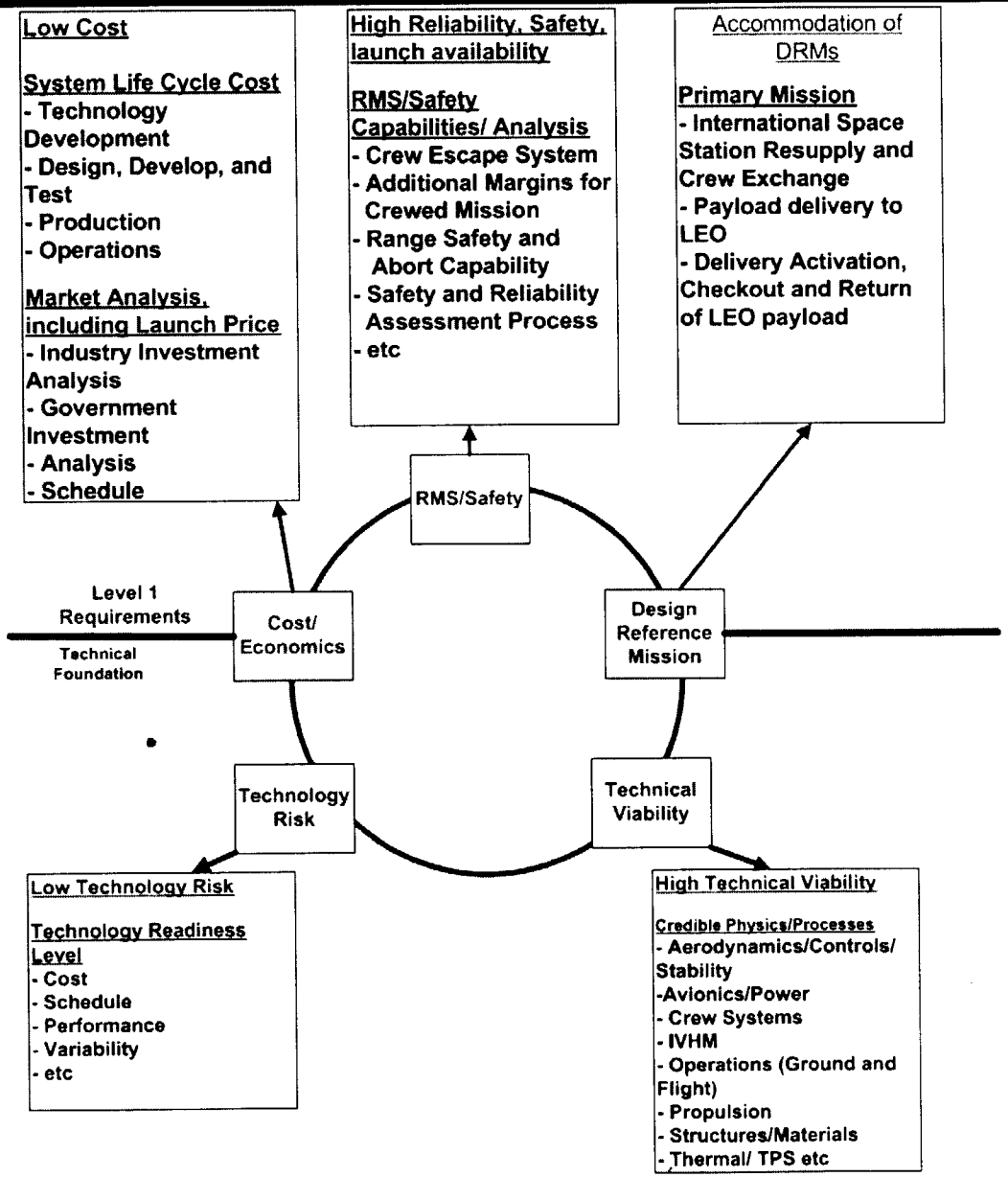
Output

- Facility Requirements
- Manpower, Personnel and Training Requirements
- Spare/Repair Parts/Consumable Requirements
- Maintenance Task Analysis Resources
- Test and Ground Support Equipment Requirements
- Packaging, handling, storage and transportation requirements
- Technical data, documentation and database requirements
- Post-production support (e.g., fielding, performance evaluation, sustaining engineering) requirements

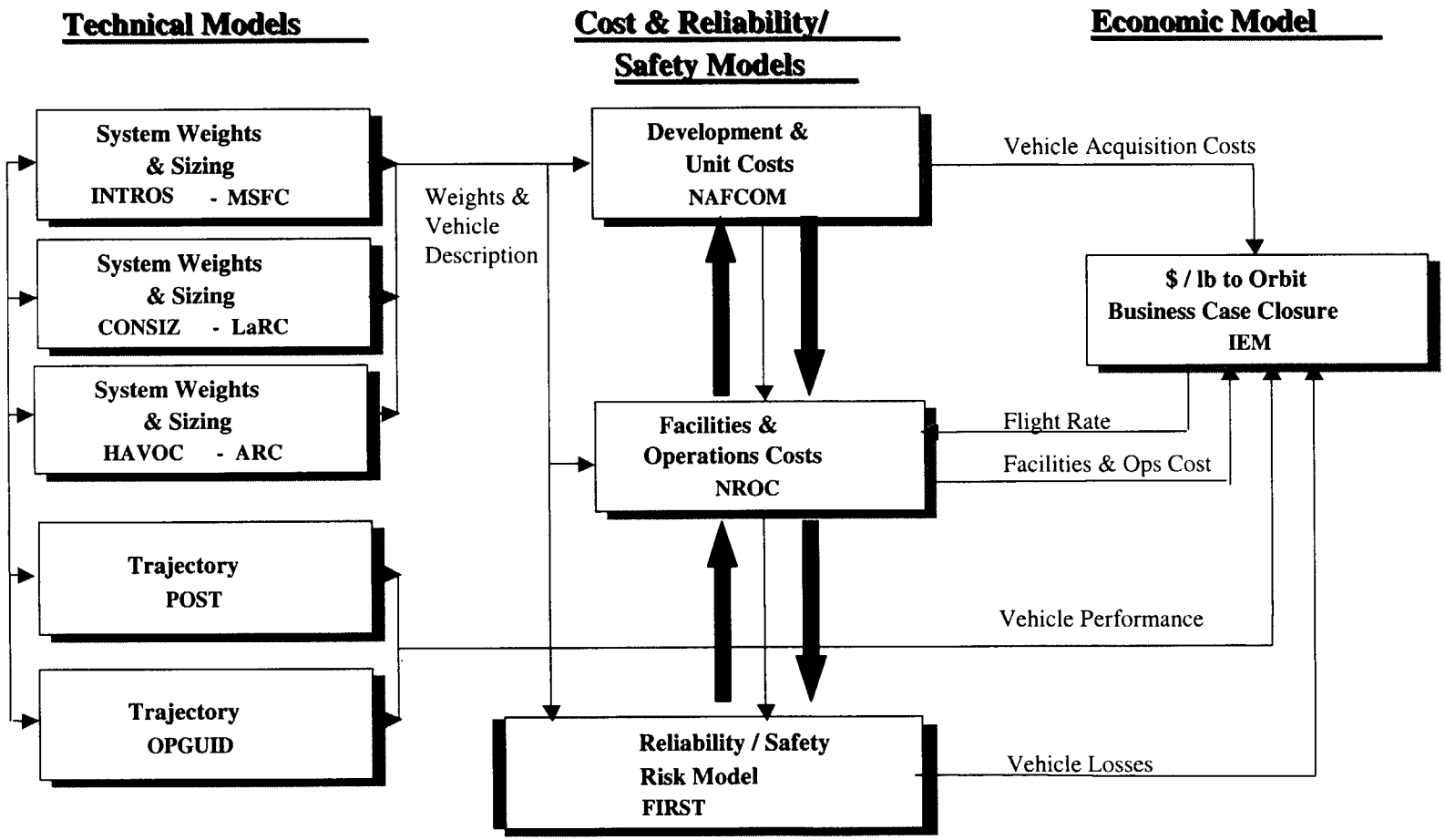
RMS Analysis and Modeling Environment

- RMS Engineering is part of SE&I Organization
- RMS Modeling and Analysis part of the 2GRLV Advanced Engineering Environment.
- RMS Figures of Merit (FOM) serve as relative evaluator of proposed architecture
  - Probability of LOC
  - Probability of LOV
  - Probability of LOM
  - Launch/System Availability
- RMS work within an Engineering analysis process that addresses 5 criteria:
  1. High Reliability, Safety and launch availability
  2. Low Cost
  3. Accommodation of DRM
  4. Technology Risk
  5. Technical Viability

Criteria Addressed by the Systems Analysis Process



Integrated Modeling Environment



CONCLUSION

- We have presented an integrated RMS approach that provides the pathway for a risk based and analysis based decision process that is necessary to achieve NASA's goal of significantly improving safety and reliability and reducing the life cycle cost of future LEO transportation system.